



RESEARCH
ARTICLE

Type-B Energetic Processes and Their Associated Scientific Implications

James Weifu Lee

jwlee@odu.edu

Department of Chemistry and
Biochemistry
Old Dominion University
Norfolk, Virginia, USA

SUBMITTED March 7, 2022
ACCEPTED August 15, 2022
PUBLISHED September 22, 2022

<https://doi.org/10.31275/20222517>

PLATINUM OPEN ACCESS



Creative Commons License 4.0.
CC-BY-NC. Attribution required.
No commercial use.

HIGHLIGHTS

New research reveals a new energy process that uses limitless heat energy in the environment to do useful work like creating electricity.

ABSTRACT

Recently, our work has identified two thermodynamically distinct types (A and B) of energetic processes naturally occurring on Earth. Type-A energy processes such as the classical heat engines, ATP hydrolysis, and many of the known chemical, electrical, and mechanical processes apparently follow well the second law of thermodynamics; Type-B energy processes, for example, the newly discovered thermotropic function that isothermally utilizes environmental heat energy to do useful work in driving ATP synthesis, follow the first law of thermodynamics (conservation of mass and energy) but do not have to be constrained by the second law, owing to its special asymmetric functions. In mitochondria, special asymmetric functions associated with Type-B processes comprise: 1) Transmembrane-electrostatic proton localization; 2) The transmembrane asymmetry of inner mitochondrial membrane structure with the protonic outlets of redox-driven proton-pumping protein complexes protruded away from the membrane surface by about 1–3 nm into the bulk liquid p-phase while the protonic inlet of the F_0F_1 -ATP synthase located at the transmembrane-electrostatically localized proton (TELP) layer; and 3) The lateral asymmetry of mitochondrial cristae with an ellipsoidal shape that enhances the density of TELP at the cristae tips where the F_0F_1 -ATP synthase enzymes are located in support of the TELP-associated thermotropic function. The identification of Type-B energy processes indicates that there is an entirely new world of physical and energy sciences yet to be fully explored. Innovative efforts exploring Type-B processes to enable isothermally utilizing endless environmental heat energy could help liberate all people from their dependence on fossil fuel energy, thus helping to reduce greenhouse gas CO_2 emissions and control climate change, with the goal of a sustainable future for humanity on Earth.

KEYWORDS

Thermodynamic–spatial asymmetry, isothermal environmental heat energy utilization, thermotropic function, negative entropy, transmembrane electrostatically localized protons, asymmetric biomembrane structure



Identification of Type-B Energetic Processes

Physical sciences, including chemistry and biochemistry, are intimately linked with energetics. In centuries past, probably due to monolithic thinking about the second law of thermodynamics, it was widely believed that environmental heat energy (which is the dissipated form of thermal (heat) energy, also known as latent heat or the temperature-dependent molecular thermal motion kinetic energy in the environment), could not be utilized to do useful work unless there is a temperature gradient or difference. That is also known as one of the classic rules for the second law of thermodynamics (Nikulov, 2011; Pisano et al., 2019; Sheehan, 2012). Recently, through bioenergetics elucidation studies with the transmembrane-electrostatically localized protons (TELP) theory (Lee, 2005, 2012, 2013, 2015, 2019a, 2020c; Saeed & Lee, 2018), it was surprisingly revealed that environmental heat energy can be isothermally utilized through TELP at a liquid-membrane interface to help drive ATP synthesis in many biological systems (Lee, 2017, 2018, 2019c, 2019e, 2019f, 2020b) including mitochondria (Lee, 2021b). This finding indicated that the protonic bioenergetic systems have a thermotrophic feature that can isothermally utilize environmental heat (dissipated-heat energy) through TELP with asymmetric

membrane structures to generate significant amounts of Gibbs free energy to drive ATP synthesis (Lee, 2017, 2018, 2019c, 2019d, 2019e, 2019f, 2020b). This has now led to an important discovery: there are two thermodynamically distinct types (A and B) of energetic processes naturally occurring on Earth (Lee, 2021b).

Type-A energy processes such as classical heat engines, and many of the known chemical, electrical, and mechanical processes apparently follow well the second law; Type-B energy process as exemplified by the thermotrophic function that isothermally utilizes environmental heat energy associated with TELP does not necessarily have to be constrained by the second law, owing to its special asymmetric function (Lee, 2020a, 2021b). The discovery of Type-B energy process indicates that there is an entirely new world of physics, chemistry, and biochemistry yet to be fully explored.

Key Factors in the Protonic Thermotrophic Function as a Type-B Energetic Process

We now understand that the protonic thermotrophic function as a Type-B energy process is enabled through two key factors (Figures 1 and 2): 1) transmembrane-electrostatic proton localization, and 2) the asymmetric structures of biological membranes.

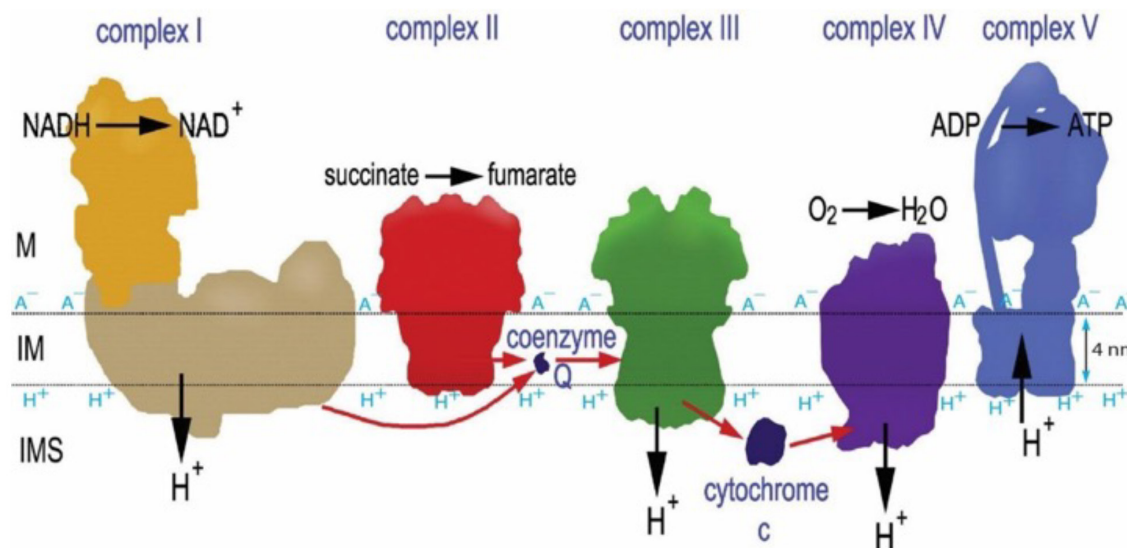


Figure 1. The transmembrane asymmetric structure is one of the key factors that enable isothermal environmental heat energy utilization as a Type-B process to do useful work in driving ATP synthesis. This figure presents the known structures of mitochondrial respiratory membrane protein complexes I, II, III, IV, and F₀F₁-ATP synthase (complex V) in relation to the location of the membrane surfaces indicated by the horizontal dotted lines. The thickness of the membrane lipid bilayer (in between the horizontal lines) is known to be approximately 4 nm, with which as a reference frame the protonic outlets of the proton pumping complexes I, III, and IV are seen to be all protruded by approximately 1–3 nm into the bulk liquid phase, while the protonic inlet of F₀F₁-ATP synthase (complex V) is located at the transmembrane-electrostatically localized proton layer along the membrane surface. Adapted from Lee (2020b), which was adapted and modified from a schematic representation of the oxidative-respiratory phosphorylation system given in Dudkina et al. (2010).

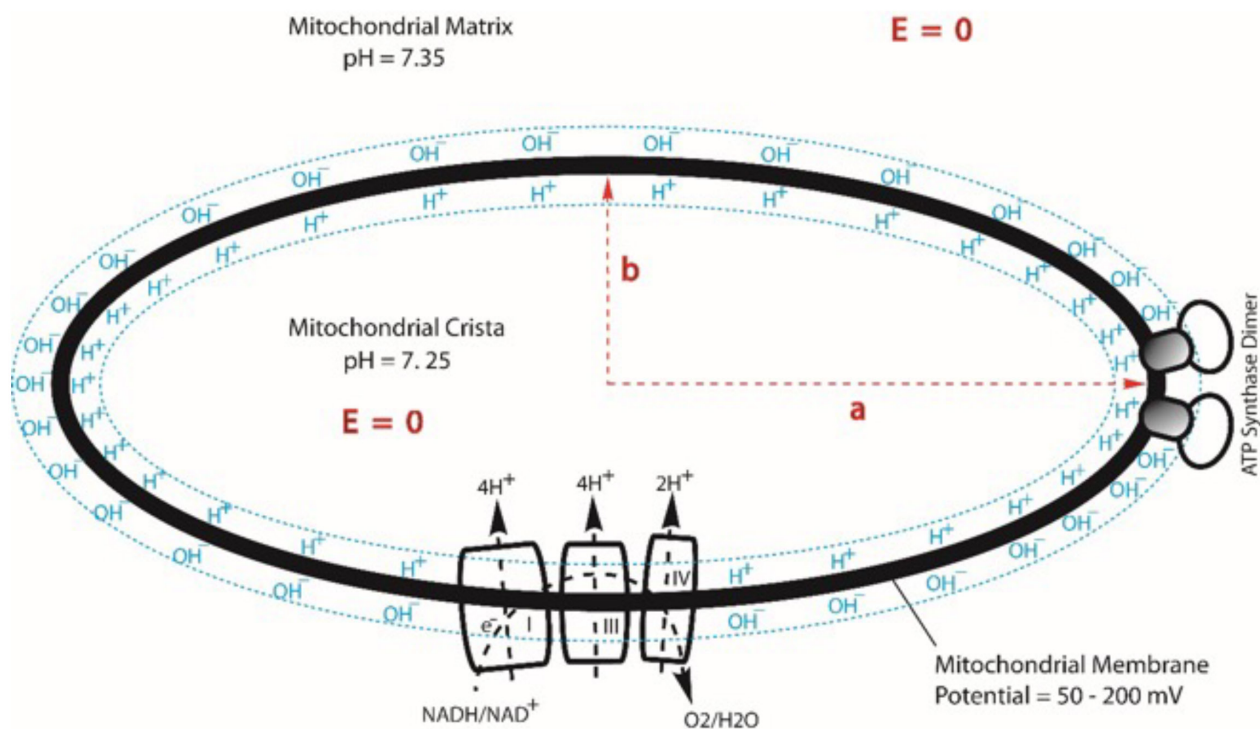


Figure 2. The protonic capacitor formation through transmembrane-electrostatic proton localization is another key factor that enables isothermal environmental heat energy utilization as a Type-B process to do useful work in driving ATP synthesis. This figure illustrates: the lateral asymmetric feature resulting from the geometric effect of mitochondrial membrane cristae, which enhances the density of transmembrane electrostatically localized protons at the cristae tips where the F_0F_1 -ATP synthase enzymes reside in contrast to those at the relatively flat membrane region where the proton pumping complexes I, III, and IV stay as shown in a cross-section for an ellipsoidal-shaped mitochondrial crista. Adapted from Lee (2020c).

The transmembrane-electrostatic proton localization is a protonic capacitor behavior that stems from the property of liquid water as a protonic conductor and the mitochondrial inner membrane as an insulator (Figures 1 and 2). Consequently, the creating of an excess number of protons on one side of the mitochondrial inner membrane accompanied by a corresponding number of hydroxyl anions on the other side, for instance, through the redox-driven electron-transport-coupled proton pumps across the membrane, will result in the formation of a protonic capacitor across the biomembrane as shown in Figures 1 and 2. Accordingly, the excess positively charged protons in an aqueous medium on one side of the mitochondrial inner membrane will electrostatically become localized as TELP at the liquid-membrane interface, attracting an equal number of excess negatively charged hydroxyl anions to the other side (matrix) of the mitochondrial inner membrane to form a “protons-membrane-anions capacitor structure” (Lee, 2005, 2012, 2013, 2015, 2019a, 2019c, 2020b, 2020c, 2020d). The TELP activity at the liquid-

membrane interface is now known to contribute to the amount of local protonic Gibbs free energy (ΔG_L) according to the following equation:

$$\Delta G_L = -2.3 RT \log_{10}(1 + [H_L^+]/[H_{pB}^+]) \quad (1)$$

Here, $[H_L^+]$ is the TELP concentration at the membrane-liquid interface at the positive (p)-side; $[H_{pB}^+]$ is the bulk liquid phase proton concentration at the same p -side in the mitochondria intermembrane space and cristae space; R is the gas constant; and T is the environmental temperature in Kelvin.

The ratio ($[H_L^+]/[H_{pB}^+]$) of the localized proton concentration $[H_L^+]$ at the membrane-liquid interface to the bulk liquid-phase proton concentration $[H_{pB}^+]$ at the same side in the mitochondria intermembrane space and cristae space is related to the “negative entropy change” (ΔS_L), as shown in the following quantitative expression:

$$\Delta S_L = -2.3 R \log_{10}(1 + [H_L^+]/[H_{pB}^+]) \quad (2)$$

As you can see in this local protonic entropy (ΔS_L) Equation 2, if TELP concentration $[H_L^+]$ is above zero, the entropy change (ΔS_L) is mathematically shown here as a negative number. That is, the entropy change for the isothermal environmental heat utilization function as a Type-B energy process is indeed negative as long as the localized proton concentration $[H_L^+]$ is above zero in the mitochondria.

The transmembrane asymmetric structure (Figure 1) such as the protonic outlets of proton-pumping protein complexes I, III, and IV protruded away from the membrane surface by approximately 1–3 nm into the bulk liquid *p*-phase (intermembrane space, IMS) while the protonic inlet of the ATP synthase (complex V) located rightly at the localized proton layer along the membrane surface enables effective utilization of TELP with their thermal motion kinetic energy ($k_b T$) to do useful work in driving the rotatory molecular turbine of F_0F_1 -ATP synthase for ATP synthesis. Consequently, the mitochondria can isothermally utilize the low-grade environmental heat energy associated with the 37 °C human body temperature to perform useful work driving the synthesis of ATP with TELP. Fundamentally, it is the combination of protonic capacitor and asymmetric membrane structure that makes this amazing thermotrophic (Type-B energy process) feature possible.

Furthermore, there is a lateral asymmetric feature from the geometric effect of mitochondrial cristae (a crista typically with an ellipsoidal shape is a fold in the inner membrane of a mitochondrion) that enhances the density of TELP at the cristae tips (Lee, 2020c), where the F_0F_1 -ATP synthase enzymes are located (Figure 2) in supporting the thermotrophic function. As recently reported (Lee, 2020c), the ratio of the TELP concentration at the crista tip ($[H_L^+]_{tip}^0$) to that at the crista flat membrane region ($[H_L^+]_{flat}^0$) equals the axial ratio (*a/b*) of an ellipsoidal mitochondrial crista. Consequently, for an ellipsoidal crista with a length of 200 nm and a width of 20 nm, the TELP concentration at the crista tip ($[H_L^+]_{tip}^0$) can be as high as 10 times that of the flat region ($[H_L^+]_{flat}^0$). This lateral asymmetric effect translates to a TELP-associated liquid-membrane interface pH difference of approximately one pH unit between the crista tip (ridge) and the flat region within the same crista. It is now known that the proton-pumping “respiratory supercomplexes” (complexes I, III, and IV) are situated at the relatively flat membrane regions where the TELP concentration ($[H_L^+]_{flat}^0$) is relatively lower, whereas the ATP synthase dimer rows are located at the cristae ridges (tips) where the TELP concentration ($[H_L^+]_{tip}^0$) is significantly higher, as shown in Figure 2 (Blum et al., 2019; Davies et al., 2011, 2012, 2018; Guo et al., 2018; Kühlbrandt, 2015; Lee, 2020c). Consequently, even if the

protonic outlets of complexes I, III, and IV are somehow in contact with the TELP layer at the crista flat membrane region so that their activities would be equilibrated with the redox potential chemical energy limit ΔG_{Chem} ($-22.0 \text{ kJ mol}^{-1}$), the total protonic Gibbs free energy (ΔG_T) at the crista tip can still be as high as $-27.9 \text{ kJ mol}^{-1}$ since the TELP density at the crista tip can be as high as 10 times that of the crista flat region, equivalent to an additional effective protonic Gibbs free energy of $-5.89 \text{ kJ mol}^{-1}$ owing to the crista geometric effect on TELP at the liquid-membrane interface (Lee, 2020c).

Note that when the axial ratio (*a/b*) equals unity (one) for a round sphere (symmetric), the density of TELP would be the same at any spot along the liquid-membrane interface for the entire spherical membrane system. Therefore, we now further understand that the ellipsoidal (asymmetric) vs the spherical (symmetric) shape change represents another revenue of spatial asymmetry that enables a lateral asymmetric TELP distribution along the crista liquid-membrane interface to increase TELP density at the crista tip (relative to the crista flat region) to enhance the TELP-associated thermotrophic function.

As a folksy summarizing description for the protonic capacitor, its two charge layers across the biomembrane creates a voltage, like a self-contained protonic battery (Figures. 1 and 2). The protonic battery can then drive protonic flow through the nanometer-scale molecular turbine of F_0F_1 -ATP synthase to synthesize ATP from ADP and Pi. The assembly line for the reactions of biomembrane system is illustrated in Figure 1, which depicts the various biochemical factories (Complexes I–V) that carry out these processes. Namely, Complex I, III, and IV consume redox chemical energy to pump protons across the membrane through their protruded protonic outlets (asymmetric feature) into the bulk liquid phase (to avoid contact with the TELP layer) while the protonic mouth of F_0F_1 -ATP synthase (Complex V) is rightly positioned within the TELP layer to utilize the protonic energy. Furthermore, the geometric effect of mitochondrial membrane cristae (lateral asymmetric feature) enhances TELP density at the cristae tips where the F_0F_1 -ATP synthase enzymes reside (Figure 2) for the utilization of the protonic energy to drive the synthesis of ATP that the cells can use.

Isothermal Absorption (Utilization) of Environmental Heat Energy Owing to Thermotrophy

When TELP-associated thermotrophic activities utilize mitochondrial environmental heat energy ($k_b T$) in driving the molecular turbine of F_0F_1 -ATP synthase for the synthesis of ATP from ADP and Pi, as discussed in Lee (2020b),

a fraction of the environmental heat ($k_b T$) energy may consequently be locked into the chemical form of energy in ATP molecules; and it would thus result in a small drop in the environmental temperature theoretically because of the TELP-associated isothermal environmental heat utilization.

However, in mitochondria and the cells,

there are other processes (including the glycolysis, tricarboxylic acid cycle, and the redox-driven proton-pumping electron transport activities as well as the ATP utilization processes such as ATP hydrolysis) releasing heat energy, which could mask the thermotrophic function that features as the isothermal environmental heat energy utilization process.

Therefore, the energetic phenomenon in mitochondria (and the cells) may represent an interconnected mixture of both chemotrophic and thermotrophic processes. This subtle complexity has taken a long time to be understood.

We expect that when the release of heat energy from chemical energy and metabolism is limited such as under anaerobic conditions, isothermal environmental heat utilization of thermotrophic activities could still be detected directly by monitoring heat absorption through measuring the system temperature changes. Such an isothermal environmental heat absorption (utilization) has indeed been observed in an anaerobic liquid culture of *Methanosarcina* sp. cells in the experiments conducted by the author. Experimental results demonstrated that the temperature of *Methanosarcina* liquid cell culture was observed to substantially decrease by approximately 0.10 °C, and sometimes by as much as 0.45 °C, in comparison with the control (liquid medium without cells) (Lee, 2023 in press). This is significant since it experimentally demonstrates isothermal absorption (utilization) of environmental heat energy owing to thermotrophy.

Thermotrophy-Associated Protonic Bioenergetic Systems as Type-B Energetic Processes Operate Widely in Natural Environments

The thermotrophy-associated protonic bioenergetics systems widely operate in nearly all organisms known today. It is now also clear that this special thermotrophic process associated with TELP has probably already been occurring on Earth for billions of years. Therefore, we have now identified two thermodynamically distinct types (A and B) of energy processes naturally occurring on Earth, based on their properties and whether they follow the sec-

ond law of thermodynamics or not. As mentioned before, Type-A energetic processes include glycolysis, tricarboxylic acid cycle, redox-driven electron transport, and many of the known chemical reactions and processes in our test tubes, computers, and cars that apparently follow the second law. Type-B energetic processes represented here by the thermotrophic function (Figures 1 and 2) do not have to be constrained by the second law, owing to their special asymmetric functions. That is, the second law still remains a valid law. However, it does not necessarily have to be universal, as indicated by a number of independent studies (Battail, 2009; Jennings et al., 2018; Koski et al., 2014; Lee, 1983, 2017, 2019b; Pal et al., 2014; Serreli et al., 2007; Sheehan, 2012, 2018; Sheehan et al., 2012, 2014; Vologodskii et al., 2001).

We now have at least three well-defined biosystems: mitochondria (Lee, 2021b), alkalophilic bacteria (Lee, 2020b), and methanogen *Methanosarcina* (Lee, 2023 in press) with well-corroborated scientific evidence showing the special Type-B process that perfectly follows the thermodynamic first law (conservation of mass and energy), but which are not constrained by the second law of thermodynamics. As shown in Equation 2, the entropy change (ΔS_L) for TELP-associated isothermal environmental heat utilization was calculated indeed to be a negative number. Therefore, the new understanding of the Type-B process may represent a complementary development to the second law of thermodynamics and its applicability in bettering the science of bioenergetics and energy renewal.

Type-B Energetic Processes: The Second Law of Thermodynamics Does Not Necessarily Have to Be Universal

We all understand that the second law remains an incredibly good law. However, it does not necessarily have to be absolute or universal, as indicated by well-documented independent studies (Battail, 2009; Čápek & Bok, 1999; Jennings et al., 2018; Koski et al., 2014; Lee, 1983, 2017, 2019b; Pal et al., 2014; Serreli et al., 2007; Sheehan, 2012, 2018; Sheehan et al., 2012, 2014; Vologodskii et al., 2001). The special Type-B process perfectly follows the first law of thermodynamics (conservation of mass and energy) but does not obey the second law. In other words, the TELP-associated thermotrophic function as a Type-B process clearly represents an example of a natural “second law violation,” since the Type-B process by definition is not constrained by the second law.

Note that the second law of thermodynamics was developed from the Sadi Carnot cycle (Saslow, 2020) that was based on the ideal gas law ($nRT = PV$; where P is pressure, V is volume, and n is the number of moles) where the ideal

molecular particles were assumed to have freedoms in 3-dimensional space (volume) without the consideration of any asymmetric structures. In the case of protonic bioenergetic systems, TELP (Lee, 2005, 2012, 2013, 2015, 2019a, 2019c, 2020b, 2020c, 2020d) are on a two-dimensional membrane surface with asymmetric properties, which is quite different from the assumed three-dimensional space (volume) system that the second law was based on. Therefore, one must be careful not to mindlessly apply something like the second law, which is derived from a three-dimensional space (volume) system, to a two-dimensional and/or one-dimensional system without looking into the specific facts.

Furthermore, the thermodynamic-spatial asymmetric features that may be human-made (Lee, 2021a; Mangum et al., 2021; Sheehan et al., 2014) and/or resulting from the billion years of natural evolution were not considered by the formulation of the second law per se; this is another reason that one should be careful not to apply the second law mindlessly with monolithic thinking or blindly to certain special cases involving asymmetric systems without looking into the specifics.

This type of basic scientific principle has been well communicated in the biochemistry field of enzyme kinetics. For example, the textbook Michaelis–Menten enzyme kinetics equation, like a “law,” can be very useful to analyze the mechanisms for many of the enzymes. It is also well taught in many textbooks that one must be careful not to blindly apply the Michaelis–Menten equation to certain enzymes, such as the allosteric enzyme hemoglobin, which “diverge[s] from Michaelis–Menten behavior” (Garrett & Grisham, 2013; Nelson & Cox 2013). This is due to the fact that the Michaelis–Menten equation is based on its steady-state assumption, where the concentration of the enzyme–substrate complex (ES) is assumed to quickly reach a constant value (so that $d[ES]/dt = 0$, which makes the differential equation system solvable in obtaining the Michaelis–Menten equation). Whereas, its assumption of “ $d[ES]/dt = 0$ ” and thus the Michaelis–Menten equation are not applicable to the allosteric enzyme hemoglobin. Something similar can now be said about the applicability of the thermodynamic second law: The second law is highly valuable when being properly applied to Type-A energy processes, but not necessarily for Type-B energy processes.

That is, the second law can be applied to Type-A processes such as classical heat engines, and many of the known chemical, electrical, and mechanical processes where the second law belongs. The second law should not be blindly applied to Type-B energy processes owing to their special asymmetric functions. It is important now for our scientific communities to avoid monolithic think-

ing and keep an open mind to consider Type-B processes and their related phenomena in certain physical, chemical, and/or biological processes, especially where asymmetric mechanisms are involved. The scientific communities may well benefit from the new fundamental understanding of Type-B processes uncovered in Earth’s natural environment. To avoid blind faith in the second law, the scientific community must pay attention to what this law was really based on and to better understand its limitations, which are of great scientific and practical importance.

Better Messages Regarding Type-B Energetic Processes to Educate Scientific Communities and the Public for a Shared Sustainable Future on Earth

We now understand that many of the recent scientific explorations regarding questions on the second law of thermodynamics, such as the recent studies of Sheehan et al. (2012, 2014) and Nikulov (Gurtovoi et al., 2019; Nikulov, 2011, 2021, 2022) are legitimate and excellent and thus should be encouraged in order to move the field forward. In hindsight, however, some of the phrases used in the past such as “challenging the second law of thermodynamics” (Cápek et al., 2005; Eling & Bekenstein, 2009; Nikulov, 2011; Sheehan et al., 2012) appear to be somewhat inaccurate, or did not seem to carry exactly the right messages for the scientific community. This could in part explain why so far they still have not been well received by many in the scientific community, who may feel the second law serves their research very well, and for good reasons. In fact, to many in the scientific community who may be familiar only with Type-A processes, the term “challenging the second law of thermodynamics” could be misunderstood as “challenging” the basis of their careers, which might have been built largely on classic thermodynamic second law as taught in textbooks. Consequently, some may feel upset or annoyed, with an attitude of “total disbelief,” and quite often tend to completely ignore or reject the topic.

Somewhat like the Michaelis–Menten equation that works well with many known enzymatic processes, the second law of thermodynamics is indeed an excellent law within its own assumed basis and domain (the ideal gas law-based Carnot cycle), which can well explain Type-A processes. On the other hand, if one were to blindly apply the second law to a Type-B process, then the user would be unable to see what we can now see (e.g., thermotrophic activities). This would be somewhat analogous to blindly applying the Michaelis–Menten equation to hemoglobin and failing to see hemoglobin’s beautiful allosteric cooperativity of oxygen binding activities on the enzyme essential for our life. Therefore, this author encourages the use

of more accurate terms like “challenging the applicability (or universality) of the thermodynamic second law,” since the second law is applicable to Type-A processes but may not necessarily be applicable to Type-B processes because of their special asymmetric functions.

For a world in which the second law is now known to not be absolute, biological Type-B processes may be harnessed by innovatively mimicking thermotrophic functions to utilize limitless environmental thermal energy to do useful work such as generating isothermal electricity to power the modern electricity-based world economy. For example, a novel invention on isothermal electricity for energy renewal has now been made to generate isothermal electricity by innovatively translating the concept of the asymmetric protonic membrane capacitor-enabled Type-B process into an isothermal electrons-based power generation system, which is referred as “an asymmetric function-gated isothermal electricity generator system” that could be made into a chip device (Lee, 2019b). Its isothermal electricity power density could be so surprisingly good that a chip size of approximately 40 cm² may be sufficient to continuously power a smart mobile phone device forever (Lee, 2021b). That is, based on this invention (Lee, 2019b), novel Type-B energy technologies such as asymmetric function-gated isothermal electricity generator systems have the potential capabilities to permanently power many electric devices, electric motors, machines, and vehicles including (but not limited to) mobile phones, laptops, cars, buses, trains, ships, and airplanes utilizing limitless environmental heat energy alone without requiring any fossil fuel energy (Lee, 2021b). Therefore, innovative scientific research and development efforts in mimicking and/or creating Type-B processes (Lee, 2021b) to isothermally utilize endless environmental heat energy (Gurtovoi et al., 2019; Lee, 2019b, 2021a; Mangum et al., 2021; Sheehan et al., 2014) should be highly encouraged to help ultimately liberate all people from their dependence on fossil fuel energy, thus helping to reduce greenhouse gas CO₂ emissions and control climate change toward a common shared sustainable future for humanity on Earth.

ACKNOWLEDGMENTS

The author (Lee) thanks the editors and anonymous peer reviewers for their highly valuable and constructive review comments that made this article better. This work was supported in part by the Lee laboratory start-up research funds provided by the Department of Chemistry and Biochemistry, the College of Sciences, the Office of Research at Old Dominion University, and by the Old Dominion University Research Foundation, and also in part by a Multidisciplinary Biomedical Research Seed Funding

Grant from the Graduate School, the College of Sciences, and the Center for Bioelectrics at Old Dominion University, Norfolk, Virginia, USA. The energy renewal isothermal electricity invention (WO 2019/136037 A1) was made through a private scientific exploration effort outside Old Dominion University.

Competing interests. The author declares no competing interests.

REFERENCES

- Battail, G. (2009). Living versus inanimate: The information border. *Biosemiotics*, 2(3), 321–341. <https://doi.org/10.1007/s12304-009-9059-z>
- Blum, T. B., Hahn, A., Meier, T., Davies, K. M., & Kühlbrandt, W. (2019). Dimers of mitochondrial ATP synthase induce membrane curvature and self-assemble into rows. *Proceedings of the National Academy of Sciences of the United States of America*, 116(10), 4250–4255. <https://doi.org/10.1073/pnas.1816556116>
- Čápek, V., & Bok, J. (1999). A thought construction of working perpetuum mobile of the second kind. *Czechoslovak Journal of Physics*, 49(12), 1645–1652. <https://link.springer.com/article/10.1023/A:1022883701920>
- Čápek, V., & Sheehan, D. P. (2005). *Challenges to the second law of thermodynamics: Theory and experiment*. In *Fundamental theories of physics, an international book series on the fundamental theories of physics: Their clarification, development and application* (1st ed.), p. 146. Springer. <http://catdir.loc.gov/catdir/enhancements/fy0823/2005279051-t.html>
- Davies, K. M., Strauss, M., Daum, B., Kief, J. H., Osiewacz, H. D., Rycovska, A., Zickermann, V., & Kühlbrandt, W. (2011). Macromolecular organization of ATP synthase and complex I in whole mitochondria. *Proceedings of the National Academy of Sciences of the United States of America*, 108(34), 14121–14126. <https://doi.org/10.1073/pnas.1103621108>
- Davies, K. M., Anselmi, C., Wittig, I., Faraldo-Gomez, J. D., & Kühlbrandt, W. (2012). Structure of the yeast F₁F₀-ATP synthase dimer and its role in shaping the mitochondrial cristae. *Proceedings of the National Academy of Sciences of the United States of America*, 109(34), 13602–13607. <https://doi.org/10.1073/pnas.1204593109>
- Davies, K. M., Blum, T. B., & Kühlbrandt, W. (2018). Conserved in situ arrangement of complex I and III₂ in mitochondrial respiratory chain supercomplexes of mammals, yeast, and plants. *Proceedings of the National Academy of Sciences of the United States of America*, 115(12), 3024–3029. <https://doi.org/10.1073/pnas.1720702115>
- Dudkina, N. V., Kouril, R., Peters, K., Braun, H. P., & Boekema, M. J. (2019). Structure of the mitochondrial supercomplex I₁III₂IV. *Proceedings of the National Academy of Sciences of the United States of America*, 116(10), 4250–4255. <https://doi.org/10.1073/pnas.1816556116>

- E. J. (2010). Structure and function of mitochondrial supercomplexes. *Biochimica Et Biophysica Acta-Bioenergetics*, 1797(6–7), 664–670. <https://doi.org/10.1016/j.bbabi.2009.12.013>
- Eling, C., & Bekenstein, J. D. (2009). Challenging the generalized second law. *Physical Review D*, 79(2). <https://journals.aps.org/prd/abstract/10.1103/PhysRevD.79.024019>
- Garrett, R. H., & Grisham, C. (2013). *Biochemistry* 5th ed. (pp. 659–661), C. Garrett & R. H. Garrett, Eds. Brooks/Cole CENGAGE Learning.
- Guo, R. Y., Gu, J. K., Zong, S., Wu, M., & Yang, M. J. (2018). Structure and mechanism of mitochondrial electron transport chain. *Biomedical Journal*, 41(1), 9–20. <https://doi.org/10.1016/j.bj.2017.12.001>
- Gurtovoi, V. L., Antonov, V. N., Exarchos, M., Il'in, A. I., & Nikulov, A. V. (2019). The dc power observed on the half of asymmetric superconducting ring in which current flows against electric field. *Physica C: Superconductivity and Its Applications*, 559, 14–20. <https://doi.org/10.1016/j.physc.2019.01.009>
- Jennings, R. C., Belgio, E., & Zucchelli, G. (2018). Photosystem I, when excited in the chlorophyll Q(y) absorption band, feeds on negative entropy. *Biophysical Chemistry*, 233, 36–46. <https://doi.org/10.1016/j.bpc.2017.12.002>
- Koski, J. V., Maisi, V. F., Pekola, J. P., & Averin, D. V. (2014). Experimental realization of a Szilard engine with a single electron. *Proceedings of the National Academy of Sciences of the United States of America*, 111(38), 13786–13789. <https://doi.org/10.1073/pnas.1406966111>
- Kühlbrandt, W. (2015). Structure and function of mitochondrial membrane protein complexes. *BMC Biology*, 13. <https://bmcbiol.biomedcentral.com/articles/10.1186/s12915-015-0201-x>
- Lee, J. W. (1983). There may be thermotrophic type of life on Earth (Report by the Former Zhejiang Agriculture University, Department of Agromony, Student Research Group on Thermotroph Exploration Study). *Potential Science (Beijing)*, 1.
- Lee, J. W. (2005). A possible electrostatic interpretation for proton localization and delocalization in chloroplast bioenergetics system. *Biophysical Journal*, 88(1), 324a–325a. <https://pubmed.ncbi.nlm.nih.gov/31367684/>
- Lee, J. W. (2012). Proton-electrostatics hypothesis for localized proton coupling bioenergetics. *Bioenergetics*, 1(104), 1–8. <https://doi.org/10.4172/2167-7662.1000104>
- Lee, J. W. (2013). Electrostatically localized protons bioenergetics over Mitchell's classic chemiosmotic theory. *Biochemical & Molecular Engineering*, 2(4). <https://www.walshmedicalmedia.com/proceedings/electrostatically-localized-protons-bioenergetics-over-mitchells-classic-chemiosmotic-theory-23817.html>
- Lee, J. W. (2015). Proton-electrostatic localization: Explaining the bioenergetic conundrum in alkalophilic bacteria. *Bioenergetics* 4(121), 1–8. <https://doi.org/10.4172/2167-7662.1000121>
- Lee, J. W. (2017). Localized excess protons and methods of making and using the same. *United States Patent Application Publication No. US 20170009357 A1*(Copyright (C), 73 pp.
- Lee, J. W. (2018). Proton motive force computation revealing latent heat utilization by localized protons at a liquid-biomembrane interface. *Abstracts of Papers of the American Chemical Society*, 255. <https://www.sciencedirect.com/topics/biochemistry-genetics-and-molecular-biology/proton-motive-force>. Web of Science: 000435539905429.
- Lee, J. W. (2019a). Electrostatically localized proton bioenergetics: Better understanding membrane potential. *Heliyon*, 5(7), e01961. <https://pubmed.ncbi.nlm.nih.gov/31367684/>
- Lee, J. W. (2019b). Isothermal electricity for energy renewal *PCT International Patent Application Publication Number WO 2019/136037 A1*. <https://patents.google.com/patent/US20210067064A1/en>
- Lee, J. W. (2019c). *Localized excess protons and methods of making and using same* (USA Patent No. US 10,501,854 B2). U. S. Patent Office. [https://patents.google.com/patent/US10501854B2/en?q=Localized+excess+protons+and+methods+of+making+and+using+same+\(US+A+Patent+No.+US+10%2c501%2c854+B2\)](https://patents.google.com/patent/US10501854B2/en?q=Localized+excess+protons+and+methods+of+making+and+using+same+(US+A+Patent+No.+US+10%2c501%2c854+B2))
- Lee, J. W. (2019d). New discovery in energetics: Isothermal utilization of latent heat enthalpy by electrostatically localized protons at liquid-membrane interface. *Abstracts of Papers of the American Chemical Society*, 257. Web of Science: 000478860505806.
- Lee, J. W. (2019e). New finding in oxidative phosphorylation: Isothermal utilization of latent heat energy by electrostatically localized protons at liquid-membrane interface. *The FASEB Journal*, 33(1_supplement), 485.412–485.412. https://doi.org/10.1096/fasebj.2019.33.1_supplement.485.12
- Lee, J. W. (2019f). Physical chemistry of living systems: Isothermal utilization of latent heat by electrostatically localized protons at liquid-membrane interface. *Biophysical Journal*, 116(3, Supplement 1), 317a. <https://www.sciencegate.app/document/10.1016/j.bpj.2018.11.1719>
- Lee, J. W. (2020a). Isothermal environmental heat energy utilization by transmembrane electrostatically localized protons at the liquid-membrane interface. *ACS Omega*, 5(28), 17385–17395. <https://doi.org/10.1021/acsomega.0c01768>

- Lee, J. W. (2020b). Isothermal environmental heat energy utilization by transmembrane electrostatically localized protons at the liquid-membrane interface. *ACS Journal Omega*. <https://doi.org/10.1021/acsomega.0c01768>
- Lee, J. W. (2020c). Protonic capacitor: Elucidating the biological significance of mitochondrial cristae formation. *A Nature Research Journal: Scientific Reports*, 10(10304). <https://doi.org/10.1038/s41598-020-66203-6>
- Lee, J. W. (2020d). Protonic conductor: Better understanding neural resting and action potential. *Journal of Neurophysiology*, 124(4), 1029–1044. <https://doi.org/10.1152/jn.00281.2020>
- Lee, J. W. (2021a). Energy renewal: Isothermal utilization of environmental heat energy with asymmetric structures. *Entropy*, 23(6), 665. <https://www.mdpi.com/1099-4300/23/6/665>; https://res.mdpi.com/d_attachment/entropy/entropy-23-00665/article_deploy/entropy-23-00665-v2.pdf
- Lee, J. W. (2021b). Mitochondrial energetics with transmembrane electrostatically localized protons: Do we have a thermotrophic feature? *Scientific Reports*, 11(1). <https://www.nature.com/articles/s41598-021-93853-x>
- Mangum, J. M., Harerimana, F., Gikunda, M. N., & Thibado, P. M. (2021). Mechanisms of spontaneous curvature inversion in compressed graphene ripples for energy harvesting applications via molecular dynamics simulations. *Membranes*, 11(7). <https://www.mdpi.com/2077-0375/11/7/516>
- Nelson, D., & Cox, M. (2013). *Lehninger principles of biochemistry*, 6th Ed. (pp. 731–748). C. M. Nelson, Ed. WH Freeman.
- Nikulov, A. (2011). Observations of persistent current at non-zero resistance: Challenge to the second law of thermodynamics. *Second Law of Thermodynamics: Status and Challenges*, 1411. <https://doi.org/10.1063/1.3665235>
- Nikulov, A. V. (2021). Dynamic processes in superconductors and the laws of thermodynamics. *Physica C: Superconductivity and Its Applications*, 589. <https://www.sciencedirect.com/science/article/abs/pii/S0921453421001179>
- Nikulov, A. (2022). The law of entropy increase and the Meissner Effect. *Entropy*, 24(1). <https://www.mdpi.com/1099-4300/24/1/83>
- Pal, P. S., Rana, S., Saha, A., & Jayannavar, A. M. (2014). Extracting work from a single heat bath: A case study of a Brownian particle under an external magnetic field in the presence of information. *Physical Review E*, 90(2). <https://pubmed.ncbi.nlm.nih.gov/25215724/>
- Pisano, R., Anakkur, A., Pellegrino, E. M., & Nagels, M. (2019). Thermodynamic foundations of physical chemistry: Reversible processes and thermal equilibrium into the history. *Foundations of Chemistry*, 21(3), 297–323. <https://doi.org/10.1007/s10698-018-09324-1>
- Saeed, H., & Lee, J. (2018). Experimental determination of proton-cation exchange equilibrium constants at water-membrane interface fundamental to bioenergetics. *Water Journal: Multidisciplinary Research Journal*, 9, 116–140. <https://doi.org/10.14294/WATER.2018.2>
- Saslow, W. M. (2020). A history of thermodynamics: The missing manual. *Entropy*, 22(1). <https://www.mdpi.com/1099-4300/22/1/77/htm>
- Serrelli, V., Lee, C. F., Kay, E. R., & Leigh, D. A. (2007). A molecular information ratchet. *Nature*, 445(7127), 523–527. <https://doi.org/10.1038/nature05452>
- Sheehan, D. P. (2012). Infrared cloaking, stealth, and the second law of thermodynamics. *Entropy*, 14(10), 1915–1938. <https://doi.org/10.3390/e14101915>
- Sheehan, D. P. (2018). Maxwell zombies: Conjuring the thermodynamic undead. *American Scientist*, 106(4), 234–241. <https://www.americanscientist.org/article/maxwell-zombies-conjuring-the-thermodynamic-undead>
- Sheehan, D. P., Garamella, J. T., Mallin, D. J., & Sheehan, W. F. (2012). Steady-state nonequilibrium temperature gradients in hydrogen gas-metal systems: Challenging the second law of thermodynamics. *Physica Scripta*, T151. <https://iopscience.iop.org/article/10.1088/0031-8949/2012/T151/014030>
- Sheehan, D. P., Mallin, D. J., Garamella, J. T., & Sheehan, W. F. (2014). Experimental test of a thermodynamic paradox. *Foundations of Physics*, 44(3), 235–247. <https://doi.org/10.1007/s10701-014-9781-5>
- Vologodskii, A. V., Zhang, W. T., Rybenkov, V. V., Podtelezchnikov, A. A., Subramanian, D., Griffith, J. D., & Cozzarelli, N. R. (2001). Mechanism of topology simplification by type II DNA topoisomerases. *Proceedings of the National Academy of Sciences of the United States of America*, 98(6), 3045–3049. <https://www.pnas.org/doi/10.1073/pnas.061029098>